High Speed Digital Lines routed on non-metallic Spacecraft structures

High Speed Digital Lines routed on non-metallic Spacecraft structures

M. Nicoletto[1], D. Boschetti[2], P. Savi[3]
[1] Thales Alenia Space - Domain Exploration and Science Italy Engineering and Advanced Studies: Electrical System and EMC, 10146 Turin, Italy
[2] Thales Alenia Space - Domain Exploration and Science Italy Engineering and Advanced Studies: Electrical System and EMC, 10146 Turin, Italy
[3] Politecnico di Torino: Department of Electronic and Telecom. (DET), 10129 Turin, Italy

***Abstract*—Space missions and satellites are critical in terms of data distribution. On-board spacecraft it is necessary to have a data-handling network that connects instruments, mass-memory, processors, downlink telemetry, and other on-board sub-systems. Alluminium is used when a low-inductance and low-resistance ground path for fault currents and for currents induced by electromagnetic interference (EMI) is required. Standards such as SpaceWire (SpW) offer high-speed, low-power, simplicity, relatively low implementation costs, and architectural flexibility. These characteristics make SpW ideal for many space missions. In this paper, the electromagnetic interference which occurs when standard aluminium panels are replaced by lighter materials, like Carbon-Fiber-Reinforced polymer (CFRP), is analyzed. The parameters used for this assessment are the radiated E-field from high speed digital lines such as the SpW and the Low-Voltage Differential Signal (LVDS).**

***Index Terms*—spacecraft; spacewire; digital high speed line; LVDS; carbon fiber; CFRP; grounding.**

I. Introduction

Space Agencies are pushing for the future use of lightweight structures in which honeycomb outer sheets are made of Carbon-Fiber-reinforced polymer (CFRP) materials [1]. The specific resistivity of CFRP is a factor of 2000 higher than the value of aluminium; therefore, high current densities inside the CFRP material and current induced by electromagnetic interference should be avoided. Furthermore, highly conductive carbon fiber surfaces could produce an unwanted capacitance that can compromise the performance due to significant noise pickup. Based on this considerations, in many space mission of the recent past, the advantages in terms of mass saving has been neutralized by the use of additional metallic items to implement an artificial grounding plane over the CFRP parts. The items that contribute to this specific function are typically referred to as a "grounding rail network". The main purpose of this grounding rails is to provide a low DC resistance path to units placed on non-conductive or partially conductive structures. For this reason, the "grounding rail network" should be designed to sustain the DC fault current return. A second desirable function of a grounding rail plane is to provide a low-inductive path for AC currents.

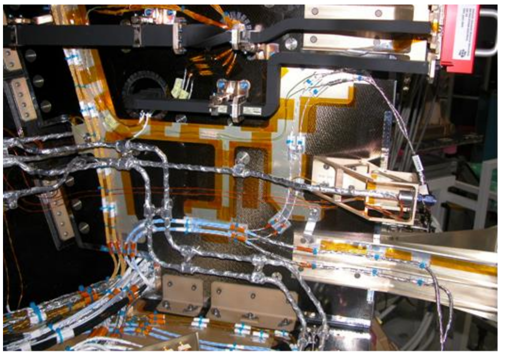

Figure 1. Grounding Rail (sketch of a segment).

On the other hand, grounding rails of greather length, have a significant inductance, and may be therefore inefficient for achieving the second goal for frequencies above about 10MHz. A previous study [2] investigated the effect of a line routed on a CFRP reference plane with and without aluminium grounding rails. The results indicate that the inductance of the grounding network is predominantly determined by the CFRP sheet and not by the aluminium grounding rails.

By dealing with digital high speed data-links, like SpaceWire (SpW) [9], the grounding strategies adopted play an essential role in controlling common mode current and minimizing electromagnetic interference (EMI).

The aim of this paper is to evaluate the radiated E-Field from a SpW link, in the presence of three different grounding planes. The first is an aluminium plane with a 2.5:1 ratio between length and width. The second is a plane made of

CFRP. The third is a long strip (2.5x0.03x0.001 m) routed on top of a CFRP panel. This last case corresponds to a typical implementation of a grounding rail network used on recent space missions. To estimate the electrical properties of a carbon fiber plane and its behavior to minimize radiated EMI, an electromagnetic model was developed by using CST Studio Suite™. The data measured were used to define the conductivity tensor of the CFRP.

II. Grounding networks for satellite applications

The bonding methods can be classified in two main typologies: direct and indirect. In direct bonding, the junctions are permanently fixed together without the need of additional joints. A lower impedance path is thus obtained, thereby increasing the electromagnetic compatibility (EMC) performances. Therefore, direct bonding is preferable, but in many cases indirect bonding is unavoidable (i.e. unit installed on partially/non- conductive surfaces like CFRP).

The grounding network - commonly made of strips or foils of aluminium, in order to reduce the inductance of the ground connection and the common mode current - is an additional item of the satellite and it is composed of grounding rails routed under the bundles, or ground planes which are mounted on the facesheet. This solution, however, is not very flexible when the routing of cable bundles has to be adapted for late design modifications.

Measurements performed on test benches or real Spacecraft have shown that the E-field radiated from low-voltage differential signaling (LVDS), a generic interface standard for high-speed data transmission) in free space is not negligible, even if dealing with differential signals. In typical space applications, the levels of Radiated E-field should be in the range 50 to 10 dBµV/m [3], measured at room temperature and using unitary cable length. This value can be increased when some of these contributions are involved:

- Extended temperature range.
- 100 m cable length in-phase signals.
- Local resonances in the cavity.
- Common mode driven by the LVDS drivers skew.
- Contributions from all synchronized signal lines.

Local resonances, cable length and temperature range are parameters that depend on the application. Skew reduction, as well as the synchronization of signal lines, can be controlled and verified more easily. At the same time, the first step for minimizing the common mode at Spacecraft level consists of properly applying adequate grounding, shielding and bonding techniques.

III. Results

Any changing voltage or current is a source of emissions. Periodic changes produce continuous emissions. All electronic systems are controlled by a continuous, more or less constant frequency generator, the ‘clock’, and thus become sources of continuous emissions. High speed digital lines use signals that change quickly from one state to another and minimize the intermediate levels whose digital states are indeterminate. Such short rise and fall times further add to the emissions produced.

A. *Modelling of a Carbon fiber reference plane*

Composite materials have a very detailed structure in which there are many parameters to take into account. The intricate details of these materials cannot be modeled on a large structure and must be replaced with equivalent multi-layer anisotropic thin panels [5].

In the case of CFRP materials for example, they consists of layers composed of laminates in which several plies are rotated to improve mechanical strength. These plies are made of carbon fiber and are impregnated in an epoxy resin matrix; a typical value for fiber diameter is 10 µm and in each ply there are about 25 fibers. An epoxy/carbon fiber composite generally comprises 57% in volume of carbon fiber. The thickness of the inter-laminate epoxy layer (M21) may suffice to electrically insulate the consecutive carbon fiber layer. The thickness of each carbon fiber layer is around 200 µm while the M21 interlayer is approximately 35 µm thick. For these reasons the carbon fiber M21 shows poor conductivity in the transversal direction.

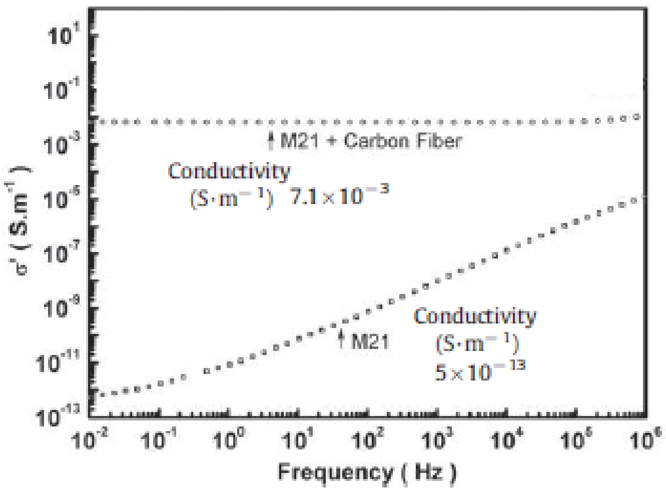

Figure 2. Complex conductivity for M21 epoxy resin and for carbon fiber composite in z direction [4].

First, a single anisotropic layer was simulated. To this end, a unit cell composed of two graphite fibers impregnated in an epoxy resin matrix was taken into account. In order to obtain the equivalent model conductivity tensor (Fig. 3), a plane wave with parallel and orthogonal polarization with respect to the fiber direction was considered. This tensor was used to find the equivalent conductivity of each layer considered isotropic and homogenous. Finally, 8 layers with a thickness of 276 µm rotated 45 degree with respect to each other were simulated in order to obtain the equivalent model of a 2mm carbon fiber sheet.

Equivalent carbon fiber conductivity based on test data confirmed the validity of the equivalent model and the adopted conductivity tensor equal to (40000, 200, 1) S/m. The equivalent conductivity of any isotropic layer is equal to 7633S/m [5]. Based on these considerations, multi-layer anisotropic thin panel material with different anisotropic material properties and thickness can be used to replace the CFRP efficiently.

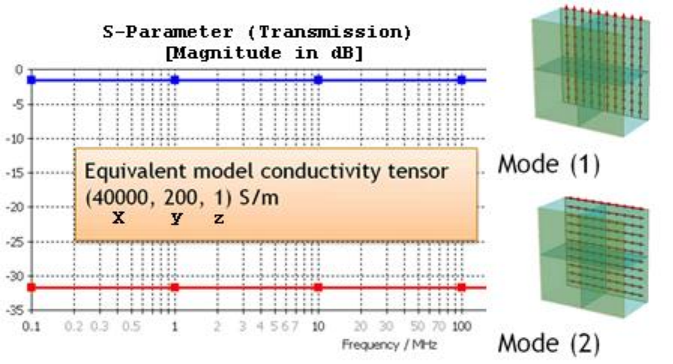

Figure 3. S-Parameters and conductivity tensor; 1 for transverse direction (blue) , 2 for filament direction (red) [5].

B. Radiated E-Field simulation

In order to compare the radiated E-field for the three ground planes under analysis in a representative and reproducible configuration, the geometry of a measurement test set-up was considered to obtain the geometry used in the simulation.

According to [1], a generic device under test has to be installed on a ground plane that reproduces the actual installation. Ground planes should be 2 m² or larger in area with the smaller side no less than 75 cm. When the equipment under test (EUT) is installed on a conductive composite ground plane, the surface resistivity of the actual installation has to be used. The measurement antennas are placed 1 m from the front edge of the test setup boundary, above the floor ground plane as shown in Fig. 4.

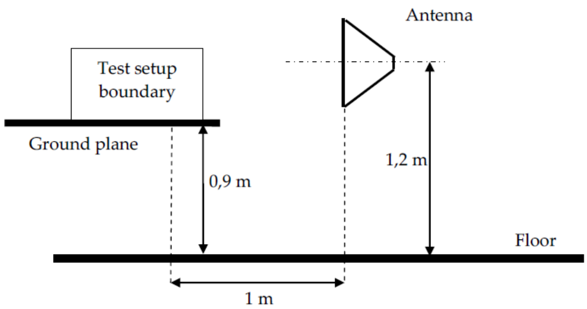

Figure 4. Electric field radiated emission - Antenna positioning [1].

For these reasons, the geometry adopted in the simulation for the computing of the E-field radiated consists of a far-field probe positioned one meter from the cabling (see Fig. 5).

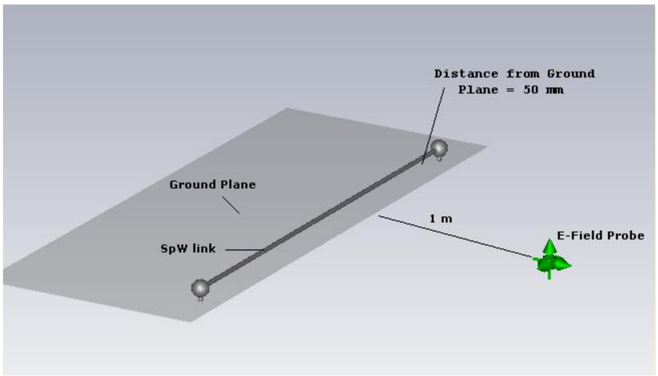

Figure 5. Simulation geometry.

Furthermore, in the simulation, the signal characteristics (amplitude, skew, time schedule, protocols, etc.) are consistent with the measurement standards [9]. The simulated input signal is shown in Fig. 6 and its parameters are reported in Tab. 1.

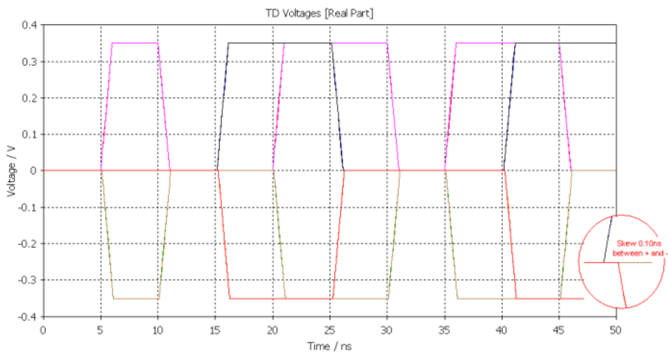

Figure 6. Signal time schedule.

	SpaceWire	
Signal	***Data***	***Strobe***
Pulse sequence	0100110110	0001100011
t_{rise}	1 ns	1 ns
t_{fall}	1 ns	1 ns
Frequency	200 Mbps	200 Mbps
Amplitude	350 mV	350 mV
Skew	0.10 ns	0.10 ns

Table 1. SpaceWire signal parameters.

The E-field levels computed, expressed in dBµV/m, are shown in Fig 7, 8 and 9.

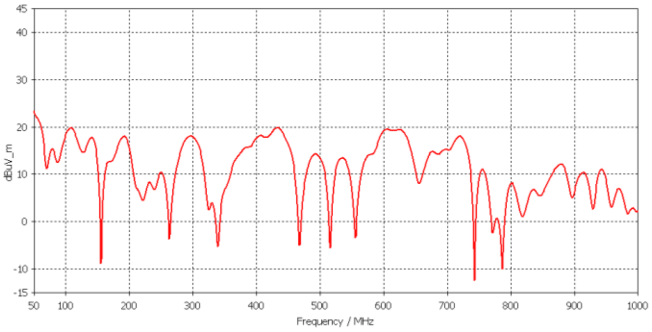

Figure 7. Radiated E-field from a SpW links (100MHz) - Case 1, Ground plane represented by an aluminium layer (dimensions 2.5 x 1x 0.003 m).

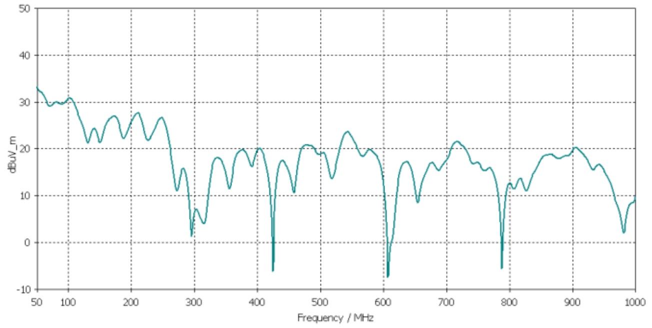

Figure 8. Radiated E-field from a SpW links (100MHz) - Case 2, Ground plane represented by a CFRP panels (dimensions 2.5 x 1x 0.003 m).

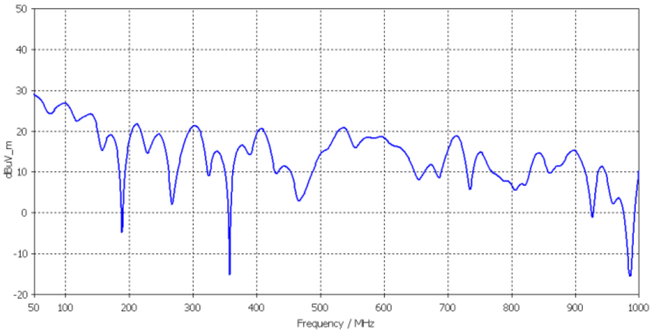

Figure 9. Radiated E-field from a SpW links (100MHz) - Case 3, Ground plane represented by a typical gorunding rail network segment on top of a composite structure.

The grounding plane made of aluminium (Case 1), due to its intrinsic lower impedance, represents the best solution in terms of minimization of the radiated E-Field, in the whole frequency range analyzed. The pure CFRP plane, compared with the one implementing a grounding rail network, induces higher levels of radiated E-field, mainly observable at lower frequencies (below 200 MHz). Nevertheless, the radiated e-field levels are well inside the typical requirements applicable to Space equipment [3]. Based on these results, CFRP panels may be used for common mode current return, avoiding the mass penalties induced by the implementation of a grounding network which tracks the entire harness.

IV. Conclusion

The analysis and results described in this paper indicate that the electrical conductivity of carbon fiber can be used to simplify the grounding network. Fault currents may be properly managed by a dedicated network of low resistance conductors that, do not need to be tracked along the entire harness, inducing a mass saving.

It should be remarked that the transversal conductivity is very low because the thickness of the inter-laminar epoxy layer could be enough to electrically insulate the successive carbon fiber layer. Future space missions may implement scientific Instruments which require for minimizing the S/C generated E-field levels below 50 MHz For these specific cases, it is therefore necessary to increase the electrical conductivity of the epoxy matrix to improve the transversal conductivity across the composite section. The characteristics of the “new” material are similar to metallic materials. In this case, ground rails are not necessary and in order to divert fault current an external path as conductor or wire is sufficient.

Carbon nanotubes (CNTs) provide the level of conductivity of an epoxy resin filled with carbon black. Due to their aspect ratio, this value is obtained for a very low weight fraction; this very low rate allows us to maintain the mechanical properties of epoxy matrix for a relatively small weight gain. A previous study [4] reported that the final composite loading of CNTs corresponds to 1vol% to 3vol.% and permits conductivity across thickness direction approximately 10^{-4} Sm^{-1}.

Future studies will consider the characteristics of carbon fiber with CNTs [10], to realize an electromagnetic model for simulated its behavior and demonstrate that this filled composite material is comparable to conductive metallic materials.

Appendix A- High Speed Digital Line

Low-voltage differential signaling (LVDS) is a generic interface standard for high-speed data transmission. The standard [6] specifies the physical layer as an electronic interface but it does not define protocol, interconnect, or connector details because these details are application specific.

The equivalent circuit of the LVDS is shown in Fig. 1. In the driver, a current source limits output to about 3 mA, and a switch box steers the current through the termination resistor. The current returns within the wire pair, so the current loop area is small, and therefore generates the lowest amount of EMI.

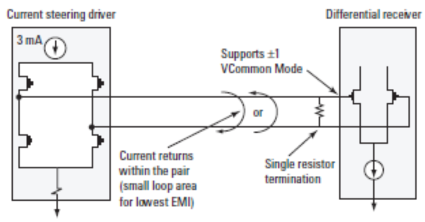

Figure 10. Equivalent circuit of the LVDS physical layer.

SpW is the Standard [9] used in the space environment that connects a SpW node to another node or to a router. Information can be transferred over both directions of the link at the same time. Bit synchronization in SpW is achieved by sending a clock signal along with the serial data. Any fluctuation in the extracted clock frequency from a constant rate is referred to as jitter. Jitter can be best defined [7] as the sum total of skews, reflections, pattern-dependent interference, propagation delays, and coupled noise that degrade signal quality. The eye pattern is a useful tool and in particularly, several characteristics are used to evaluate the quality of the signal. Noise may be coupled on a signal from several sources and is not uniform at all frequencies. The more obvious noise sources are the components of a transmission circuit that include the signal transmitter, cables, connectors and receiver. Beyond that, there is a termination dependency, skew, crosstalk, and ground reference. These aspects should be reduced because, during the propagation, part of the signal can be converted into a common mode signal. This converted signal generates EMI and induces a shutting of the eye-diagram.

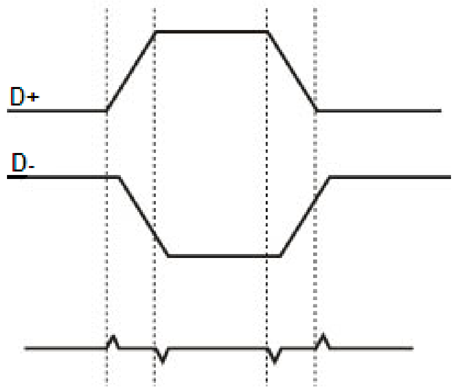

Figure 11. Common mode generated by skew

The noise generated by the skew is the main contribution to EMI. This parameter quantifies the propagation delay and is determined by some aspects that include different trace length, fiber weave effect and asymmetric placement of "vias" ground on PCB. Considering a differential transmission line with different length and input sinusoidal signals, in this situation, there is a distortion between input and output and part of the signal is converted from differential to common mode. Controlling the skew and then the jitter is important because jitter can degrade the performance of a transmission system by introducing bit errors in the digital signals

.

REFERENCES

[1] European Cooperation for Space Standardization, Standard ECSS-E-ST-20-07, C Rev. 1, "Space engineering, Electromagnetic compatibility", February 2012.

[2] M. Leininger, F. Thurecht, E. Pfeiffer, A. Ruddle, "Advanced grounding methods in the presence of carbon fibre reinforced plastic structures", Proc. 2012 ESA Workshop on Aerospace EMC, Venice, Italy, ESA SP-702, May 2012.

[3] European Cooperation for Space Standardization, Standard ECSS-E-HB-20-07A, "Space systems electromagnetic compatibility handbook", European Cooperation for Data Standardization, December 2011.

[4] Lonjon, Antoine and Demont, Philippe and Dantras, Eric and Lacabanne, "Electrical conductivity improvement of aeronautical carbon fiber reinforced polyepoxy composites by insertion of carbon nanotubes", (2012) Journal of Non-Crystalline Solids, pp. 358 (vol. 15). pp. 1859-1862. ISSN 0022-3093.

[5] D. Johns, "Electromagnetic Simulation of Composite Materials and Cable Harnesses in Aircraft", Computer Simulation technology, Webinar 20131031 1502-1, 2013.

[6] Stephen Kempainen, National Semiconductor, "Low-Voltage Differential Signaling (LVDS)", Application Note 1382-6, 2002 Agilent Technologies, Inc. 2002, 5988-4797EN.

[7] Christopher M. Miller, David J. McQuate, "Jitter Analysis of High-Speed Digital Systems", February 1995 Hewlett Packard Journal.

[8] S. Corrigan, "Skew definition and jitter analysis", February 2000 Analog and Mixed-Signal products, Analog Applications Journal, 2000.

[9] European Cooperation for Space Standardization, Standard ECSS-E-ST-50-12C, "SpaceWire, Links, Nodes, Routers and Networks", Issue 1, European Cooperation for Space Data Standardization, February 2003 (formerly ECSS-E-50-12A, February 2003.

[10] De Rosa I M, Sarasini F, Sarto M S, Tamburrano A: EMC Impact of Advanced Carbon Fiber/Carbon Nanotube Reinforced Composites for Next-Generation Aerospace Applications. *IEEE Trans. on Electromagnetic Compatibility,* 50:556-563 (2008).